ASTROPHYSICS OF PLANET FORMATION

Concise and self-contained, this textbook gives a graduate-level introduction to the physical processes that shape planetary systems, covering all stages of planet formation. Writing for readers with undergraduate backgrounds in physics, astronomy, and planetary science, Armitage begins with a description of the structure and evolution of protoplanetary disks, moves on to the formation of planetesimals, rocky, and giant planets, and concludes by describing the gravitational and gas dynamical evolution of planetary systems. He provides a self-contained account of the modern theory of planet formation and, for more advanced readers, carefully selected references to the research literature, noting areas where research is ongoing.

The second edition has been thoroughly revised to include observational results from NASA's *Kepler* mission, *ALMA* observations and the *JUNO* mission to Jupiter, new theoretical ideas including pebble accretion, and an up-to-date understanding in areas such as disk evolution and planet migration.

PHILIP J. ARMITAGE is a professor in the Department of Physics and Astronomy at Stony Brook University and he leads the planet formation group at New York's Center for Computational Astrophysics. He teaches classes on planet formation to advanced undergraduate and graduate students, and has lectured on the topic at summer schools worldwide.

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SECOND EDITION

PHILIP J. ARMITAGE
Stony Brook University and
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Preface

The study of planet formation has a long history. The idea that the Solar System formed from a rotating disk of gas and dust – the *Nebula Hypothesis* – dates back to the writings of Kant, Laplace, and others in the eighteenth century. A quantitative description of terrestrial planet formation was already in place by the late 1960s, when Viktor Safronov published his now classic monograph *Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets*, while the main elements of the core accretion theory for gas giant planet formation were developed in the early 1980s. More recently, new observations have led to renewed interest in the problem. The most dramatic development has been the identification of extrasolar planets, first around a pulsar and subsequently in large numbers around main-sequence stars. These detections have allowed us to start to assess the Solar System's place amid an extraordinary diversity of extrasolar planetary systems. The advent of high resolution imaging of protoplanetary disks and the discovery of the Solar System's Kuiper Belt have been almost as influential, the former by providing direct information about the initial conditions for planet formation, the latter by highlighting the role of dynamics in the early evolution of planetary systems.

My goals in writing this text are to provide a concise introduction to the classical theory of planet formation and to more recent developments spurred by new observations. Inevitably, the range of topics covered is far from comprehensive. The emphasis is firmly on the *astrophysical* aspects of planet formation, including the physics of the protoplanetary disk, the agglomeration of dust into planetesimals and planets, and the dynamical interactions between those bodies and the disk and among themselves. The information that can be deduced from study of the chemical and geological makeup of Solar System bodies is discussed in places where that information is particularly pertinent, but this book is intended to complement rather than to replace textbooks on planetary science and cosmochemistry.

This book began as a graduate course that I taught at the University of Colorado in Boulder, for which the prerequisites were undergraduate classical physics and mathematical methods. The primary readership is beginning graduate students, but most of the text ought to be accessible to undergraduates who have had some exposure to Newtonian mechanics and fluid dynamics. Although the mathematical demands are relatively elementary, the text does not shy away from covering modern theoretical developments, including those where research is very much still ongoing. Especially in these areas I provide extensive references to the technical literature to enable interested readers to explore further.

The decade since the first edition was published has seen further dramatic advances. NASA's *Kepler* mission has revolutionized our understanding of the population of relatively small extrasolar planets, while high resolution images of protoplanetary disks with *ALMA* have identified a wealth of largely unexpected structure. The chapter on observations has required major revision. On the theory side there has been intense interest in several processes that were either unknown or under-appreciated (at least by me) ten years ago, including pebble accretion, disk winds, the streaming instability, and vortices. Those omissions have been remedied. I have also added reference material on dynamics, and thoroughly revised the existing text to reflect both new thinking in areas such as planetary migration and my own teaching preferences.

My understanding of planet formation has been shaped by the many collaborators that I have had the privilege to work with. I am indebted to them, to the students in Boulder and at various summer schools who have informed my thinking about how best to teach the subject, and to the colleagues who have provided feedback and encouragement. Lastly, my thanks to Dada, whose unwavering support brought this new edition to fruition.